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SOME ASPECTS OF ENERGY TRANSFER IN THE ELECTRODE AND SETTLING SECTIONS OF AN ARC-HEATED WIND TUNNEL

By

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ARO, Inc.

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ARNOLD ENGINEERING DEVELOPMENT CENTER

AIR FORCE SYSTEMS COMMAND

UNITED STATES AIR FORCE

NOTICES

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FOREWORD

Appreciation is expressed to those members of the Research Branch who assisted the author with the experimental work. Particular thanks go to G. D. Arney, Jr., D. E. Boylan, J. T. Miller, W. H. Sims, and R. F. Armstrong.

ABSTRACT

A calorimetric investigation of certain energy transfer processes in the settling region of an arc-heated wind tunnel has been made. The effects of anode length and diameter on heat-transfer rates in the stilling chamber have been studied for a range of flow conditions. A radiation-cooled heat shield for use in the stilling chamber has been proposed and evaluated. A 20-percent reduction in the stilling chamber heat loss and a five-percent gain in overall efficiency are indicated with the installation of a suitable heat shield.

PUBLICATION REVIEW

This report has been reviewed and publication is approved.

D. R. Eastman, Jr. — Jean A. Jack

Donald R. Eastman, Jr.	**Jean A. Jack**
DCS/Research	**Colonel, USAF**
	DCS/Test

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ILLUSTRATIONS

NOMENCLATURE

D^*	Diameter of sonic throat
H_o	Total enthalpy measured downstream of throat, Btu/lbm
$\dot{m}$	Mass flow rate, lbm/hr
p_o	Stilling chamber stagnation pressure, psia
p_o'	Impact pressure measured downstream of normal shock, microns of mercury
T_o	Theoretical stagnation temperature upstream of aerodynamic nozzle
x	Axial distance in test section
y	Radial distance in test section

1.0 INTRODUCTION

1.1 PREVIOUS CALORIMETRIC STUDIES

The initial results of a calorimetric study of the thermodynamic properties of the flow in the Low-Density, Hypervelocity (LDH) Wind Tunnel are presented in Ref. 1. The LDH tunnel is a continuous-flow, high-enthalpy wind tunnel in operation at the von Kármán Gas Dynamics Facility (VKF), Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), US Air Force. A complete description of the LDH tunnel is given in Ref. 2.

It was concluded in Ref. 1 that, provided certain minimum requirements of settling section geometry were met, it was possible to accurately predict the total enthalpy of the flow through the aerodynamic throat from a knowledge of the mass flow rate, throat area, and stagnation pressure upstream of the throat. This experimental investigation was conducted with the aid of the total mass flow calorimeter shown in Fig. 1. After the usefulness of this device was successfully demonstrated, it was then felt that additional investigations into other aspects of certain energy transfer processes in the arc-heated wind tunnel could be conducted using the total calorimeter. The purpose of this report is to describe the results of these additional calorimetric investigations.

1.2 STATEMENT OF THE PROBLEM

The operation of a high-enthalpy wind tunnel requires some device which can be used to heat the working fluid to high temperatures. In the LDH tunnel, a Thermal Dynamics Model U-50 plasma generator is used as the energy source. The gas to be heated flows axisymmetrically over the cathode and is constricted as it passes through the non-rotated arc column and the combination nozzle and anode. The power supply is a 40-kw direct current unit, although less than 20 kw is normally required during tunnel operation.

In the present case, from the aerodynamic standpoint, the plasma is undesirable as a working fluid because of the complications that would exist in conducting studies of aerodynamic phenomena in an ionized stream. Therefore, generation of a plasma is merely a means of producing an end result, namely a high-enthalpy gas at near-equilibrium conditions.

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It would be highly desirable to isolate the operation of the plasma torch from the performance characteristics of the other tunnel components. In one sense, this isolation is accomplished by the process which occurs in the stilling chamber, as evidenced in Ref. 1. However, in the broader sense, the operating performance of the tunnel itself is greatly affected by the performance of the plasma torch – stilling chamber combination. The present investigation was initiated to increase the overall effectiveness of the heating process while maintaining the performance of the tunnel.

The energy addition process takes place in the immediate vicinity of the arc-heater electrodes. The mechanism of this heating process is not well understood. The empirical, cut-and-try procedures used in the development of most arc heaters reflect this lack of understanding. The extreme environment renders the most basic properties of the working fluid immeasurable if not indefinable by usual methods. Estimates of the "temperature" in various plasma jets, obtained by spectroscopic and other methods, range from 4000 to 26, 000°K according to Ref. 3.

Following the energy addition process, it is desirable that there occur a process in which the free electrons, ions, and dissociated molecules recombine and approach equilibrium conditions before entering the aerodynamic nozzle. This recombination is exothermic and requires the release and removal of a certain quantity of energy as heat. In the ideal case, no more energy than that released in the recombination reaction need be removed from the working fluid. However, since the working fluid must be confined within some container whose walls must be cooled to maintain structural integrity, the amount of heat actually removed becomes somewhat greater than ideal, especially when the container is long enough to ensure complete mixing.

The problems associated with improving the overall effectiveness of the plasma torch – stilling chamber combination fall into two categories: those associated with reducing the input power required to heat the working fluid at a given rate, and those associated with reducing the heat lost by the working fluid in the stilling chamber. Additional criteria are that the flow conditions in the test section and the reliability of operation of the wind tunnel should not be compromised.

2.0 TEST APPARATUS AND METHOD

2.1 TOTAL CALORIMETER

The basic piece of equipment used in this study was the total mass flow calorimeter. This device was designed to duplicate, for all practical purposes, the configuration of the LDH tunnel upstream of the geometric throat of the nozzle. Downstream of the throat, in place of the tunnel test section, the calorimeter contains a heat exchanger to extract energy from the gas stream.

The upstream end of the calorimeter is flanged to receive the plasma jet nozzle. Since the gas from the plasma gun is partially ionized and dissociated, a relatively large settling region or stilling chamber is required for complete mixing, equilibrium, and recombination to be attained upstream of the aerodynamic nozzle. This upstream portion of the calorimeter consists basically of the cylindrical settling section and the converging nozzle section. These two sections are independently water cooled, and provisions are made for measuring water flow rates and temperature rises.

The downstream heat exchanger portion is also water cooled, and the water flow rate and temperature rise can be measured. The cooled gas is exhausted from the calorimeter to the vacuum pumping system. The gas temperature is measured at the heat exchanger exit.

A photograph of the complete calorimeter installation is shown in Fig. 2.

2.2 HARDWARE IMPROVEMENTS

Two tunnel hardware improvements were proposed for consideration and evaluation in the hope of accomplishing the objectives previously set forth. The first was a new anode insert holder, which allowed standardization and simplified replacement of anode inserts of various sizes. The new anode holder was an immediate and unqualified success, greatly reducing the run-to-run variation which had previously resulted from the use of non-standardized anode configurations. The non-standardized configurations were characterized by an anode insert that was sealed to the main body by silver solder. The new anode assembly is presented in Fig. 3.

The second improvement involved the addition of a radiation-cooled heat shield in the stilling chamber to reduce the heat losses to the walls of the chamber. The basic shield was a thin, stainless steel cylinder, slightly smaller in size than the internal dimensions of the stilling chamber. The intended function of the shield was to intercept the thermal radiation from the arc and the convective heat transfer from the jet so that this energy could not reach the highly cooled stilling chamber walls directly. The shield itself was cooled by thermal radiation to the stilling chamber walls. A typical shield is shown in Fig. 4. A sketch of the typical electrode - stilling chamber - heat shield configuration is presented in Fig. 5.

Several different shield configurations were considered, including a double shield, or two concentric cylinders. The double shield proved unsatisfactory because of the over-heating of the inner shield. The addition of a lip to the upstream end of the cylindrical shield proved successful in reducing heat transfer to the stilling chamber inlet flange.

Most of the test effort in this investigation was devoted to the calorimetric studies of various electrode and heat shield combinations to determine the relative merits of the proposed hardware improvements. The results of these studies are presented in the following section.

3.0 RESULTS

3.1 PRESENTATION OF RESULTS

Anode inserts having hole diameters of 0.136, 0.196, 0.220, 0.250, and 0.281 in. were tested in the calorimeter both with and without a radiation-cooled heat shield in the stilling chamber. The shield tested was a cylindrical sleeve 2.75 in. in diam and 3.25 in. long. Based on the conclusions of Ref. 1, the so-called five-inch-long stilling chamber was used. With the present anode configuration, the effective distance from the anode outlet to the nozzle sonic throat is approximately 6.25 in.

Nitrogen was used as the working fluid. The stagnation pressure in the stilling chamber normally ranged between 10.5 and 18.9 psia, corresponding to a theoretical stagnation temperature, T_o, between 1150 and 3620°K at a flow rate of 3.6 lbm/hr. The method used to determine this theoretical stagnation temperature is presented in Refs. 1 and 4.

Figure 6 presents the observed heat-transfer rates to the cylindrical portion of the stilling chamber with no heat shield installed. The corresponding heat-transfer rates with the heat shield installed are shown in Fig. 7. As one would expect, the heat-transfer rate increases as T_o increases. The heat-transfer rate is also shown to be dependent on the diameter of the plasma torch anode, with the smaller diameter resulting in the greater heat-transfer rate. A comparison of Figs. 6 and 7 reveals that the heat loss to the stilling chamber is significantly reduced by the installation of the heat shield. This comparison is more clearly seen in Fig. 8.

The heat-transfer rates to the converging nozzle section of the stilling chamber are presented in Fig. 9. This heat-transfer rate is also a function of the anode diameter and T_o. However, since the heat shield does not cover the nozzle section, it has no observable effect on the heat-transfer rates.

The total heat lost in the stilling chamber represents the sum of the heat transferred to the cylindrical section and nozzle section. It is observed in Figs. 10 and 11 that when the total heat transfer times the anode diameter is plotted logarithmically versus the theoretical stagnation temperature upstream of the nozzle, the data tend to collapse to a straight line having a slope of about 1.55. It is therefore indicated that the heat transfer in the stilling chamber varies approximately as $T_o^{1.55}$. The slope of this line is the same with and without the heat shield; the heat transfer is merely higher without the heat shield at any given T_o, as shown by the broken line in Fig. 11.

The data presented thus far represent a single flow rate, 3.6 lbm/hr. For a fixed nozzle throat area, T_o is uniquely determined when $\dot{m}$ and p_o are selected provided equilibrium, uniform flow exists at the sonic throat. In Figs. 6 through 11 it is inferred that in determining heat-transfer rates, T_o is the important parameter rather than p_o, even though both may vary. The data in Fig. 12 were obtained by changing both $\dot{m}$ and p_o in the same ratio to hold T_o constant. This was done for three different values of T_o; the result was that the heat transferred to the stilling chamber was nearly constant at any given T_o and varied greatly for the different values of T_o. Therefore, the effect of $\dot{m}$ and p_o on heat transfer, at least over a small range, is much less than the effect of temperature.

In Figs. 13 and 14 the electrical input power to the plasma torch is plotted as a function of the anode diameter for the several values of T_o with and without the heat shield. The input power increases with decreasing anode diameter and, as expected, with increasing T_o. It is seen that, in general, the input power required with the heat shield is less than that required for the same condition without the heat shield. The same input power data are plotted logarithmically versus H_o in Figs. 15 and 16. The wide scatter in these plots is caused by the effect of anode diameter and other reasons yet to be discussed. The main value of these plots is that their slope indicates that the required input power to the plasma torch is roughly proportional to $H_o{}^{1.3}$ for a given configuration.

Thus far the effect of anode diameter on the plasma torch - stilling chamber performance has been established using a "standard" anode of length 1.10 in. To investigate the effect of anode length on performance, several inserts of different effective lengths were tested, each having a diameter of 0.250 in. A "long" anode was made merely by adding 0.250 in. to the downstream end of the anode. A "short" anode was made by machining a 45-deg taper in the hole at both ends of the anode. The "extra-short" anode was made by machining a 30-deg taper at both ends. These relatively simple procedures were chosen to produce an effectively shorter anode insert without requiring a major design change to the anode holder.

The results of the test of anodes of various effective lengths are presented in Fig. 17. The long anode causes a significant increase in total stilling chamber heat transfer compared to the standard length, whereas the heat transfer with the shorter anodes is only slightly less than that with the standard length.

It was previously stated that any proposed change in the plasma torch – stilling chamber configuration should have no deleterious effects on wind tunnel flow conditions. The total enthalpy through the throat for flow with and without the heat shield is presented in Fig. 18 for comparison purposes. Each point represents the average of all data for a particular value of the ratio $\dot{m}/p_o$. On the average, the measured enthalpy with the heat shield is one to three percent less than that measured without the heat shield. Such a trend is desirable since the measured enthalpy data of Ref. 1 are generally a few percent higher than the theoretical values.

Two series of tests were conducted in the LDH tunnel to determine the effect of the heat shield on impact pressure and heat transfer to a body in the test section. The results of the impact-pressure survey in Fig. 19 show close agreement between data obtained with and without the heat shield. The results of the heat flux survey in Fig. 20 show close agreement between data obtained with and without the heat shield; the ΔT is a relative measurement of heat transferred to the heat-transfer probe.

3.2 DISCUSSION OF RESULTS

Several observations can be made at this point to allow meaningful interpretation of the results of this investigation. First, it was not the purpose of this report to present a theoretical explanation of the processes which occur in the plasma torch – stilling chamber combination. It was rather intended as a systematic experimental investigation of these processes in which certain selected variables were to be controlled.

Second, it should be stated that no precise control could be exercised over the main variable, the arc process itself. This is attested to by the fact that two pairs of identical electrodes may require quite different electrical power inputs to produce the same conditions in the stilling chamber. A single electrode pair may operate quite differently with a minute change in gap setting or with no change at all. These variations are often manifested by a change in the audible vibration frequencies emitted from the torch. Further, the input power level may creep up or down during a single run. These seemingly random variations are mentioned lest someone be tempted to base conclusions only on observed power input data or efficiency terms derived from these data. Also, it should be recognized that variations in other performance parameters may be reflections (hopefully damped) of these perturbations in the arc process.

The results clearly indicate that the processes within the stilling chamber as well as within the arc itself are affected by the configuration of the anode. The significance of the anode diameter in correlating the data in Figs. 10 and 11 is not understood. It is suggested that a change in anode diameter could change the stilling chamber heat transfer in several ways. The most obvious way is through a change in the flow patterns in the stilling chamber. Also, it is plausible that a smaller diameter anode could concentrate the arc so that the fluid is more evenly heated or excited to a higher energy level. This theory is supported by the fact that as the anode diameter is decreased, the electrical power input tends to increase by several times the amount equal to the increased stilling chamber heat transfer. This "unaccounted-for" energy must be lost to the anode cooling water as a result of the "hotter" arc. This same theory could well account for the changes attributed to the effect of anode length; that is, the longer the anode, the "hotter" the arc.

Observations made with several different heat shields in the LDH tunnel give an indication of the flow pattern within the stilling chamber itself. Portions of the shield may be visually observed through a quartz window in the side of the stilling chamber. A small diameter shield glows red hot over most of its surface. A larger diameter shield glows red hot only on the downstream half of its length. These observations suggest that the main flow from the plasma torch diverges in a conical pattern and impinges where the shield is luminous. The heat flux in the downstream portion of the stilling chamber is therefore considerably greater than in the upstream portion.

4.0 CONCLUSIONS

On the basis of the results which have been presented, it is concluded that an anode having a hole diameter of about 0.250 in. is the optimum for use in the LDH tunnel. A smaller diameter increases the power requirements and cooling load, while a larger diameter tends to make the natural fluctuations of the arc more severe. The standard anode length should not be increased. A shortened anode holder would be helpful in evaluating a further decrease in anode length.

The radiation-cooled heat shield appears to be successful in reducing the stilling chamber heat loss. It is apparent from the energy quantities involved that the overall gain in efficiency is roughly five percent, small enough to be hidden in many instances by the usual run-to-run variation in power input. However, the stilling chamber heat loss is reduced by about 20 percent with the installation of a suitable heat shield.

By the very nature of the equipment involved, it must be emphasized that the results of this investigation may be applied quantitatively only to identical plasma torch – stilling chamber configurations and qualitatively only to configurations which are reasonably similar to the present one.

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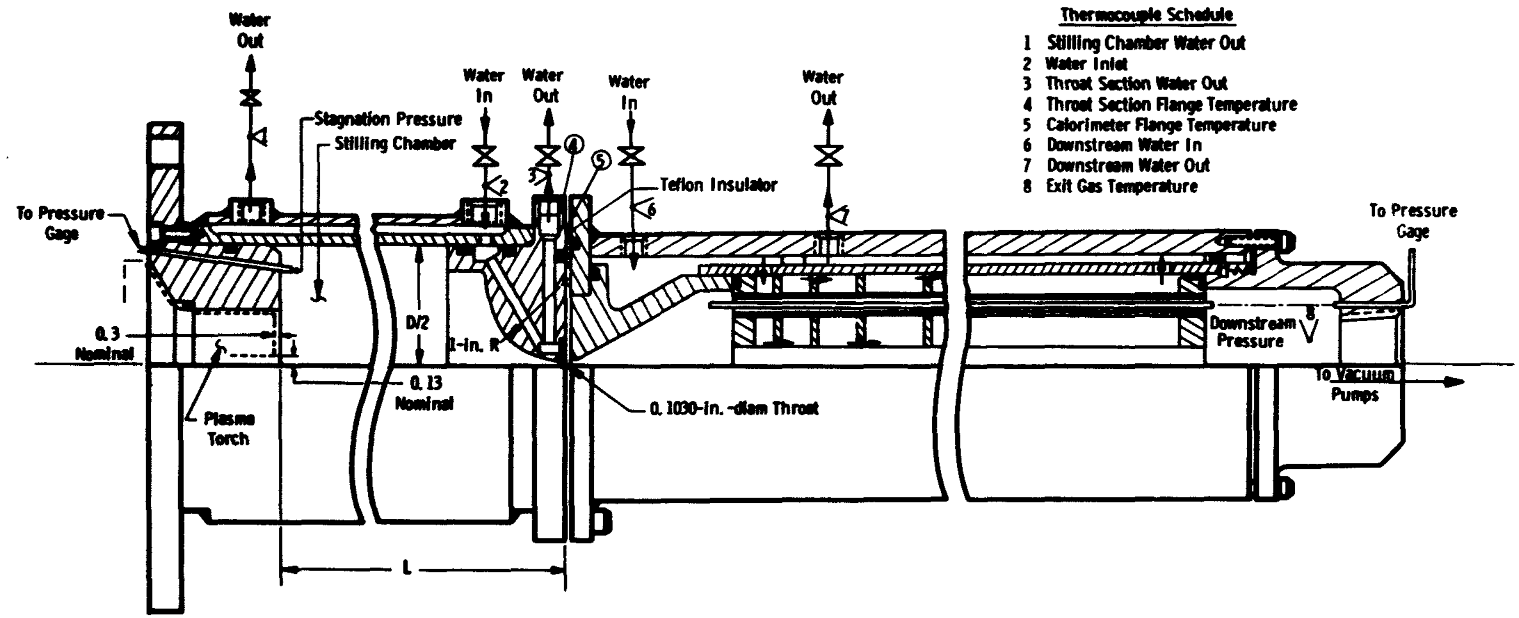


Fig. 1 Total Calorimeter

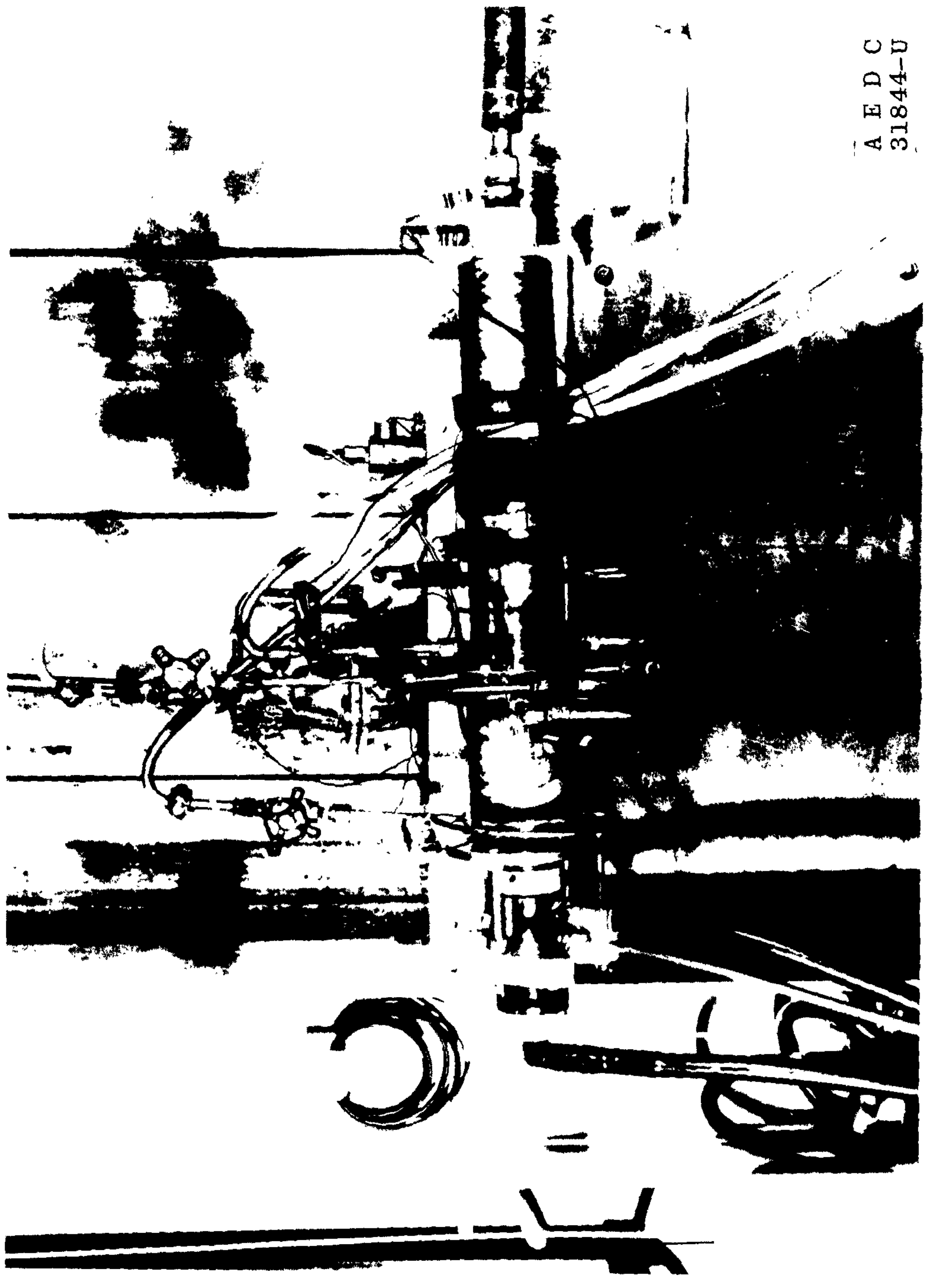
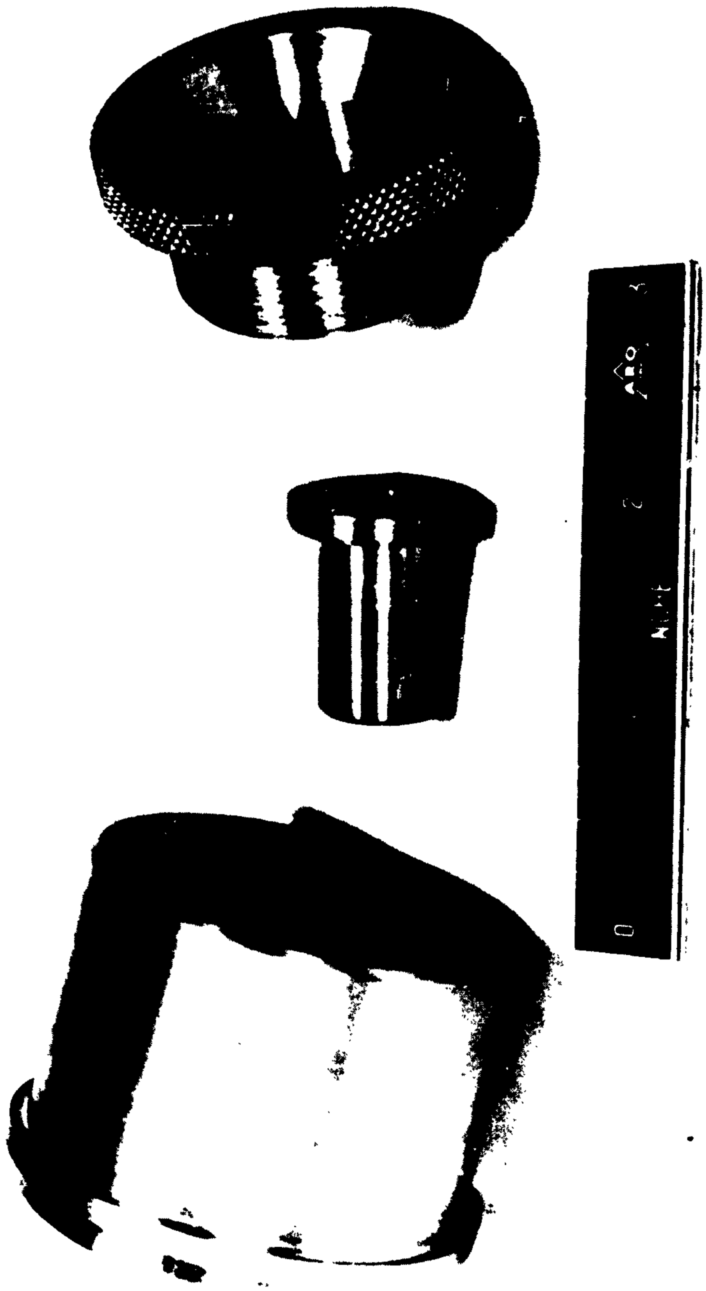


Fig. 2 Calorimeter Installation



A E D C
31102-U

Fig. 3 New Anode Assembly

A E D C
31846-U

Fig. 4 Radiation-Cooled Heat Shield

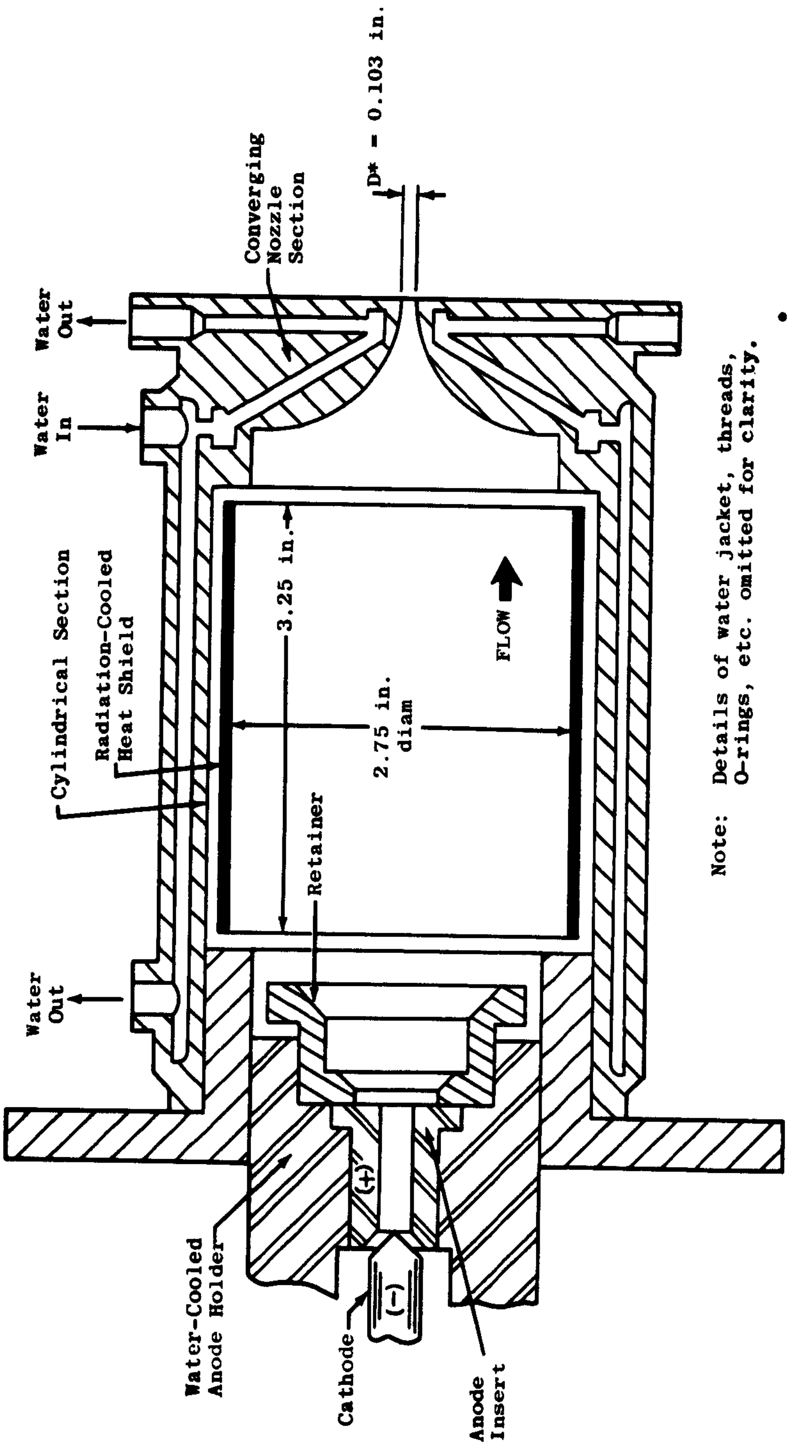


Fig. 5 Typical Electrode – Stilling Chamber – Heat Shield Configuration

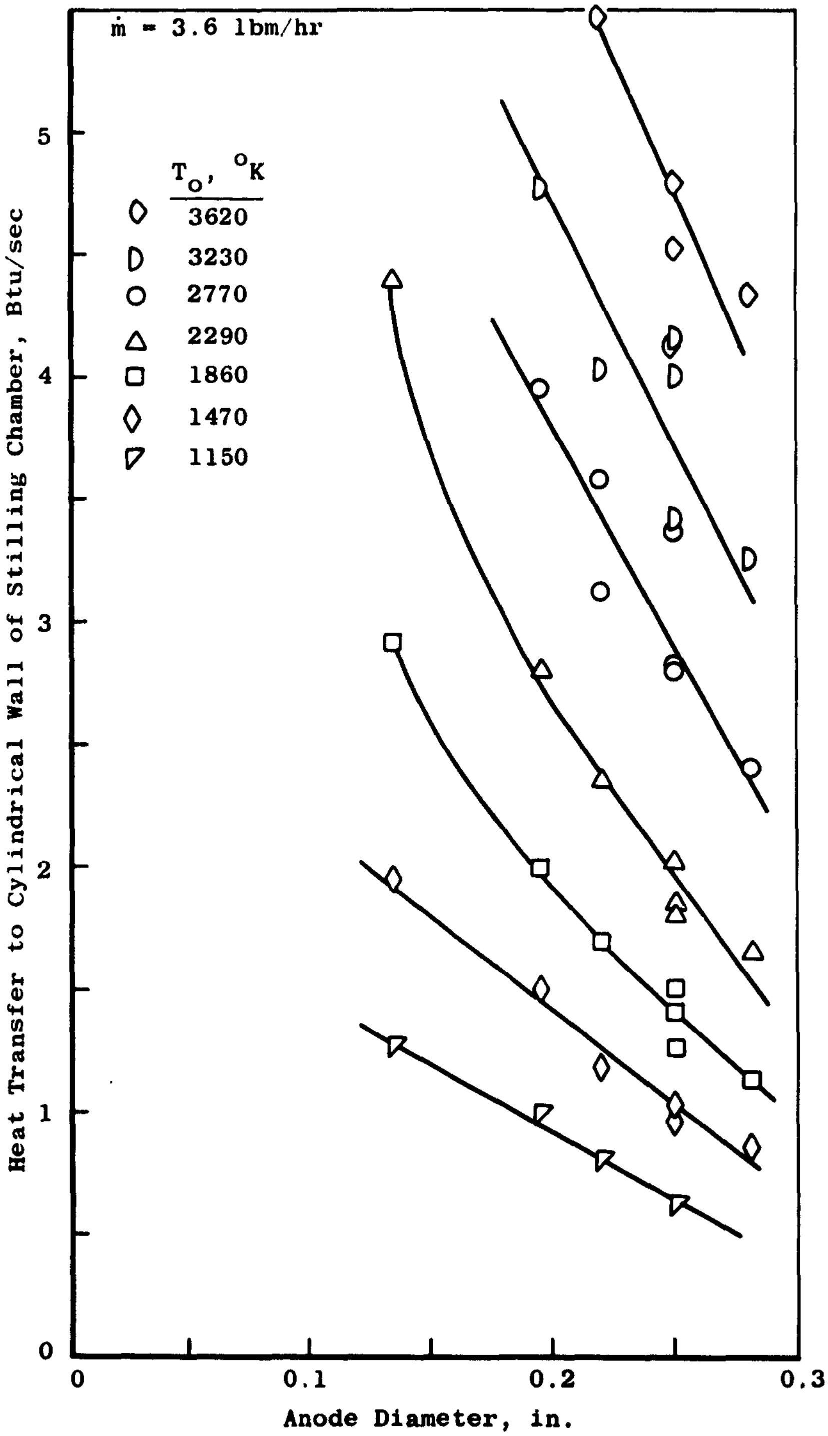


Fig. 6 Effect of Anode Diameter on Stilling Chamber Heat Transfer without Heat Shield

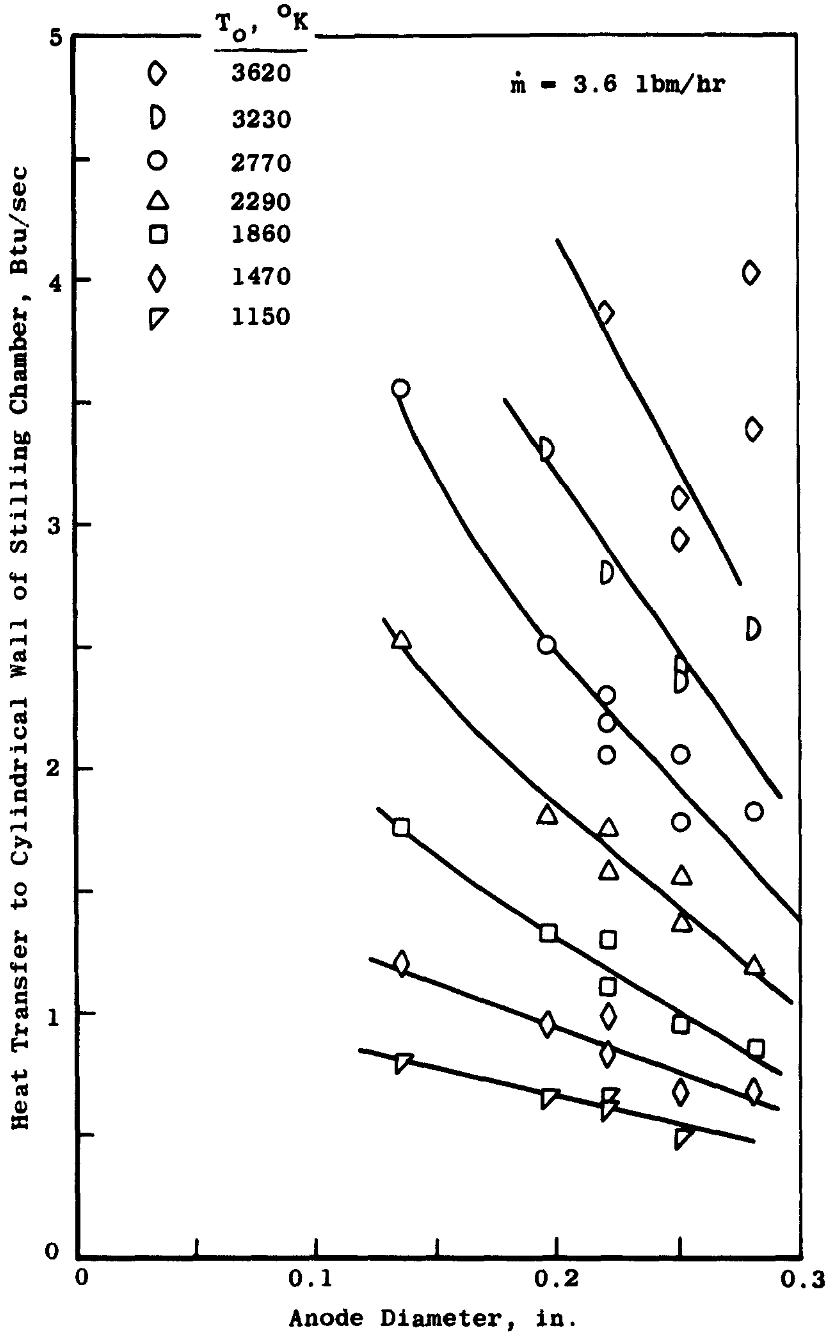


Fig. 7 Effect of Anode Diameter on Stilling Chamber Heat Transfer with Heat Shield

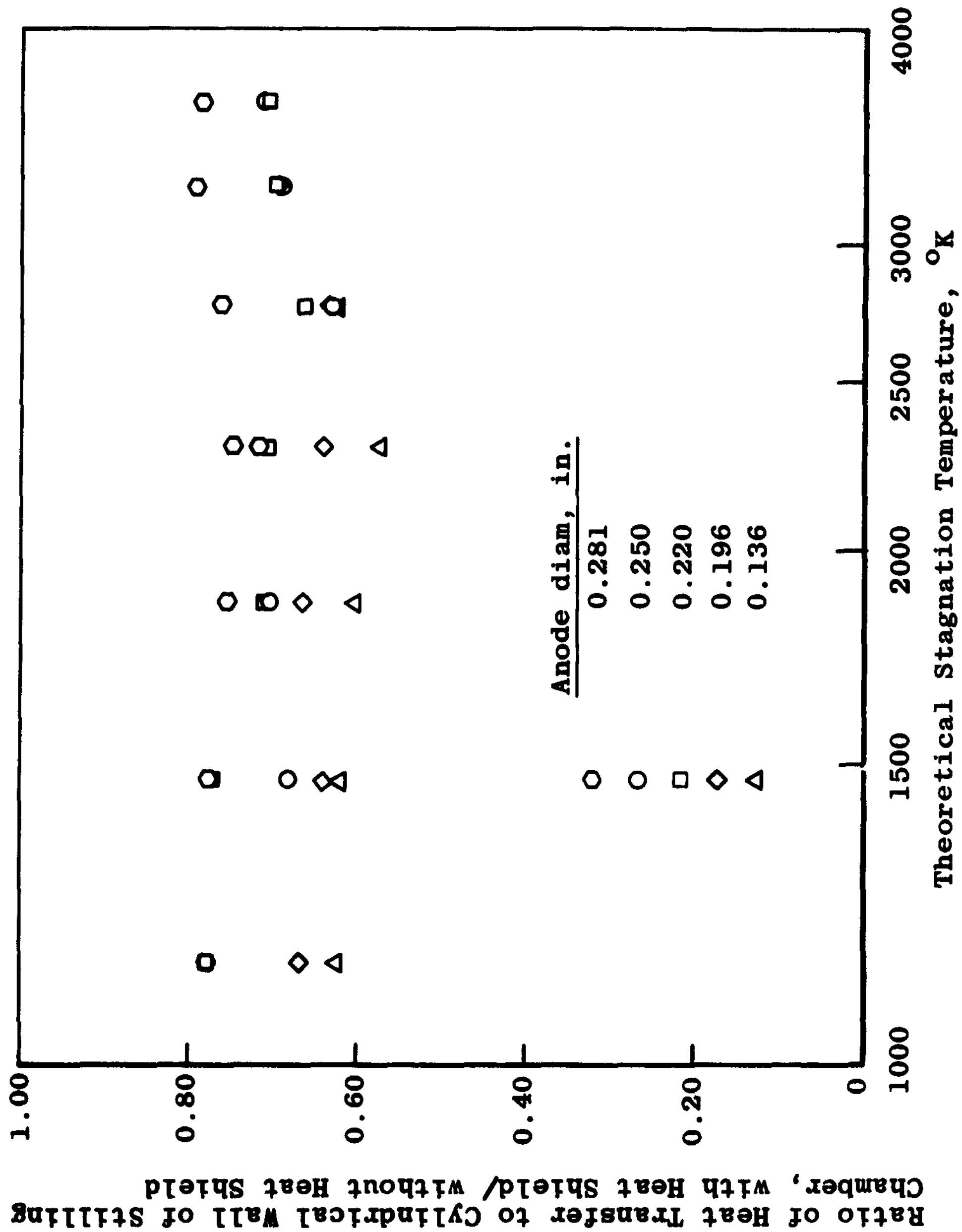


Fig. 8 Comparison of Stilling Chamber Heat Transfer with and without Heat Shield

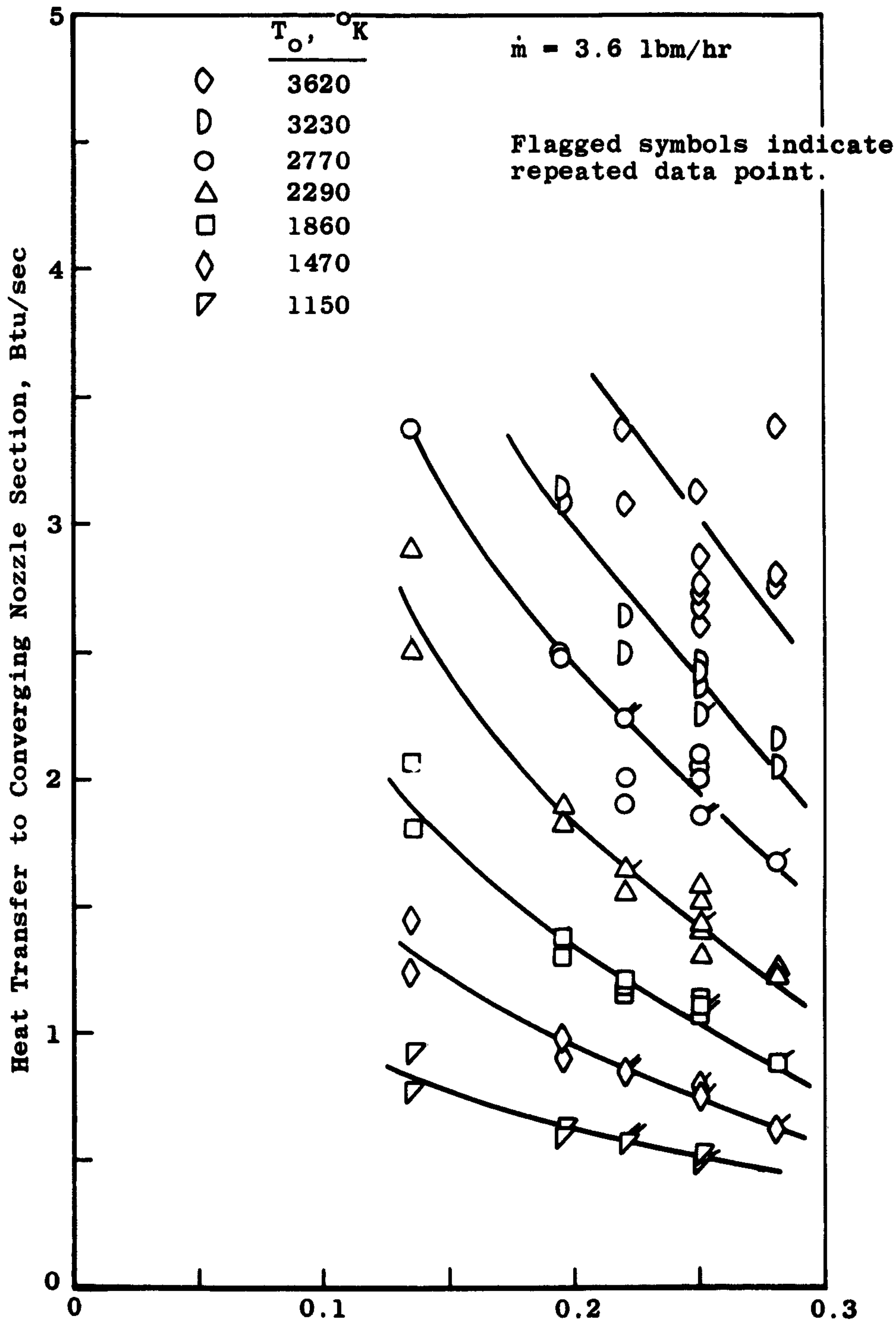


Fig. 9 Effect of Anode Diameter on Nozzle Section Heat Transfer

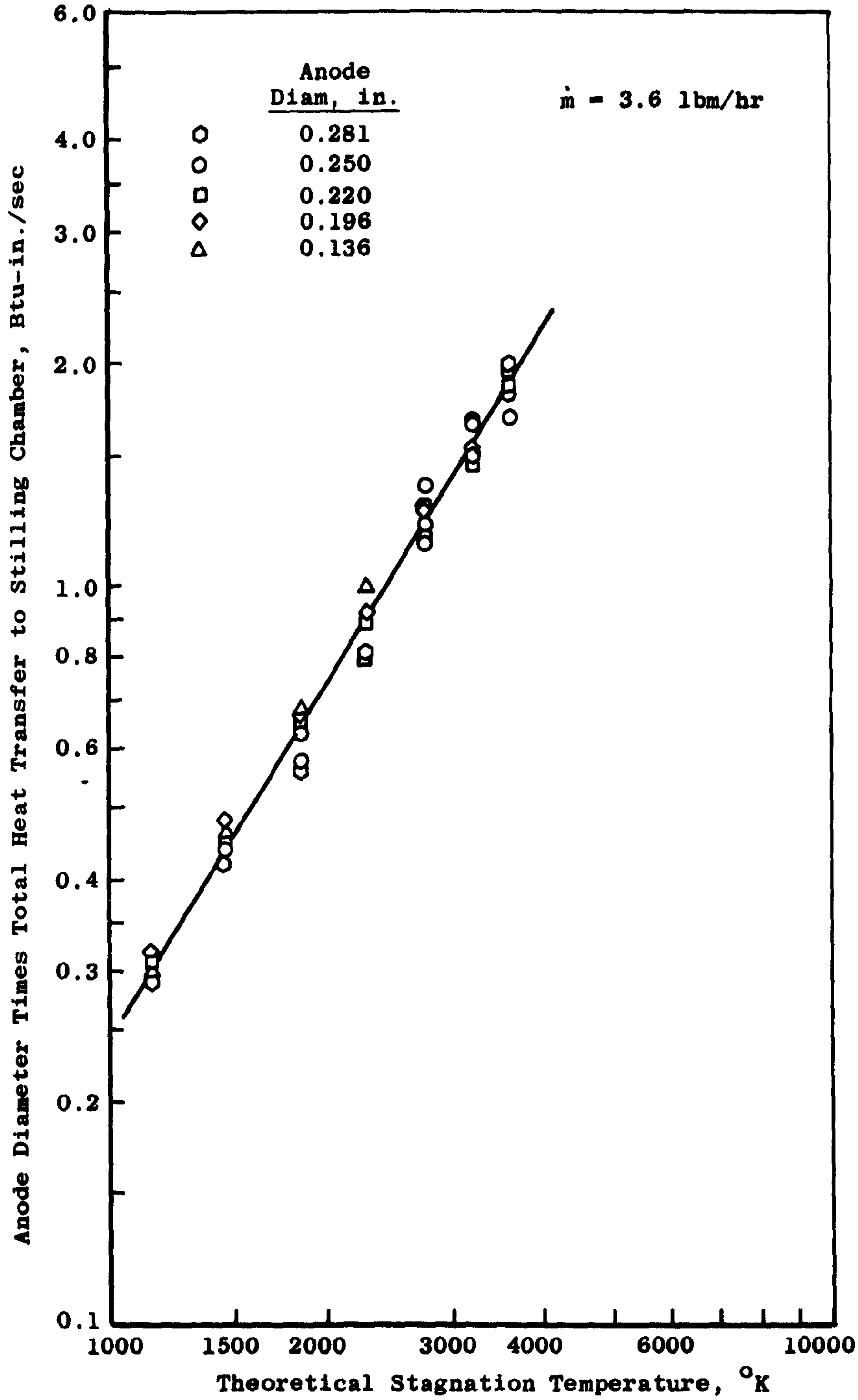


Fig. 10 Effect of T_o on Stilling Chamber Heat Transfer without Heat Shield

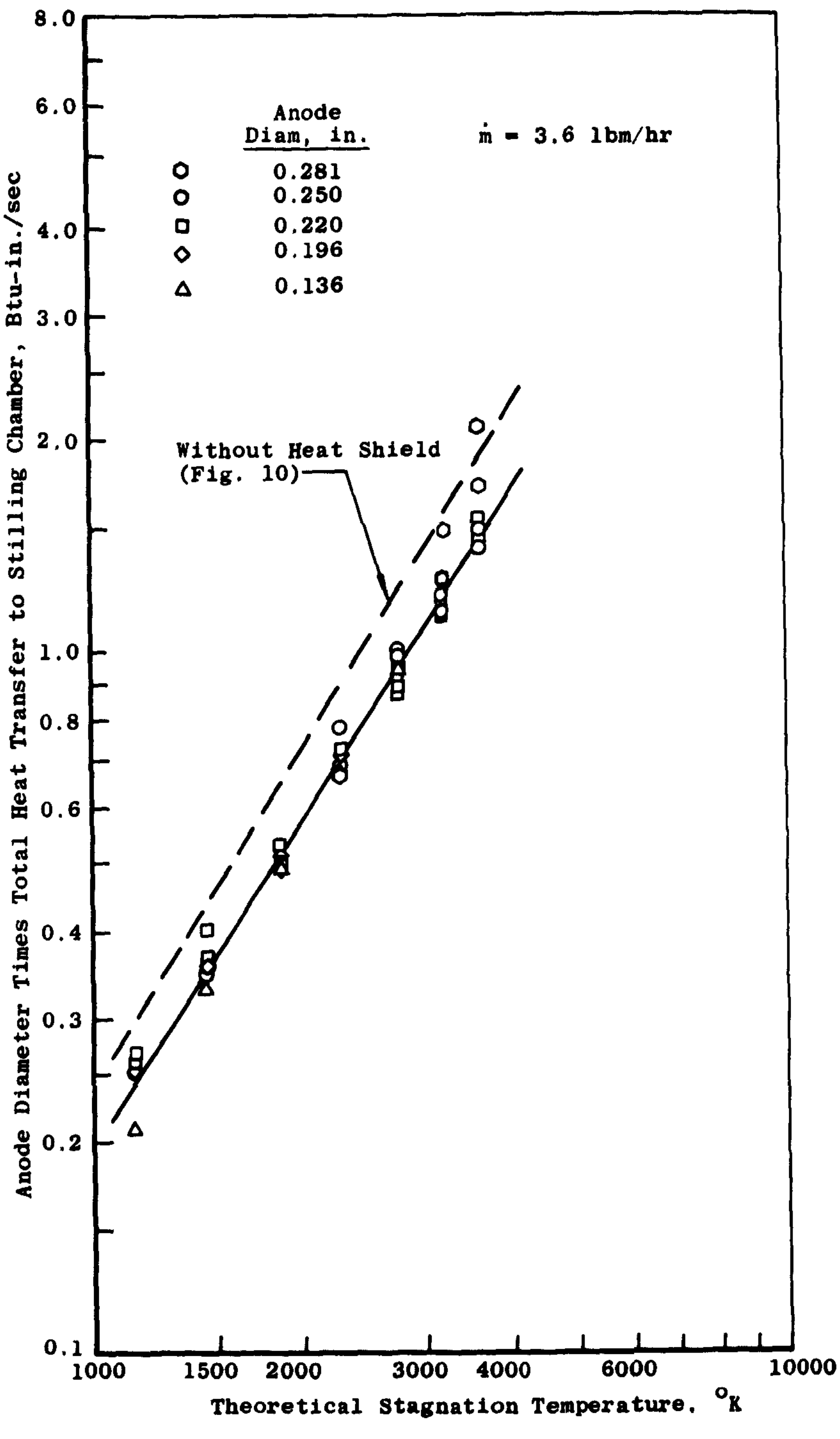


Fig. 11 Effect of T_o on Stilling Chamber Heat Transfer with Heat Shield

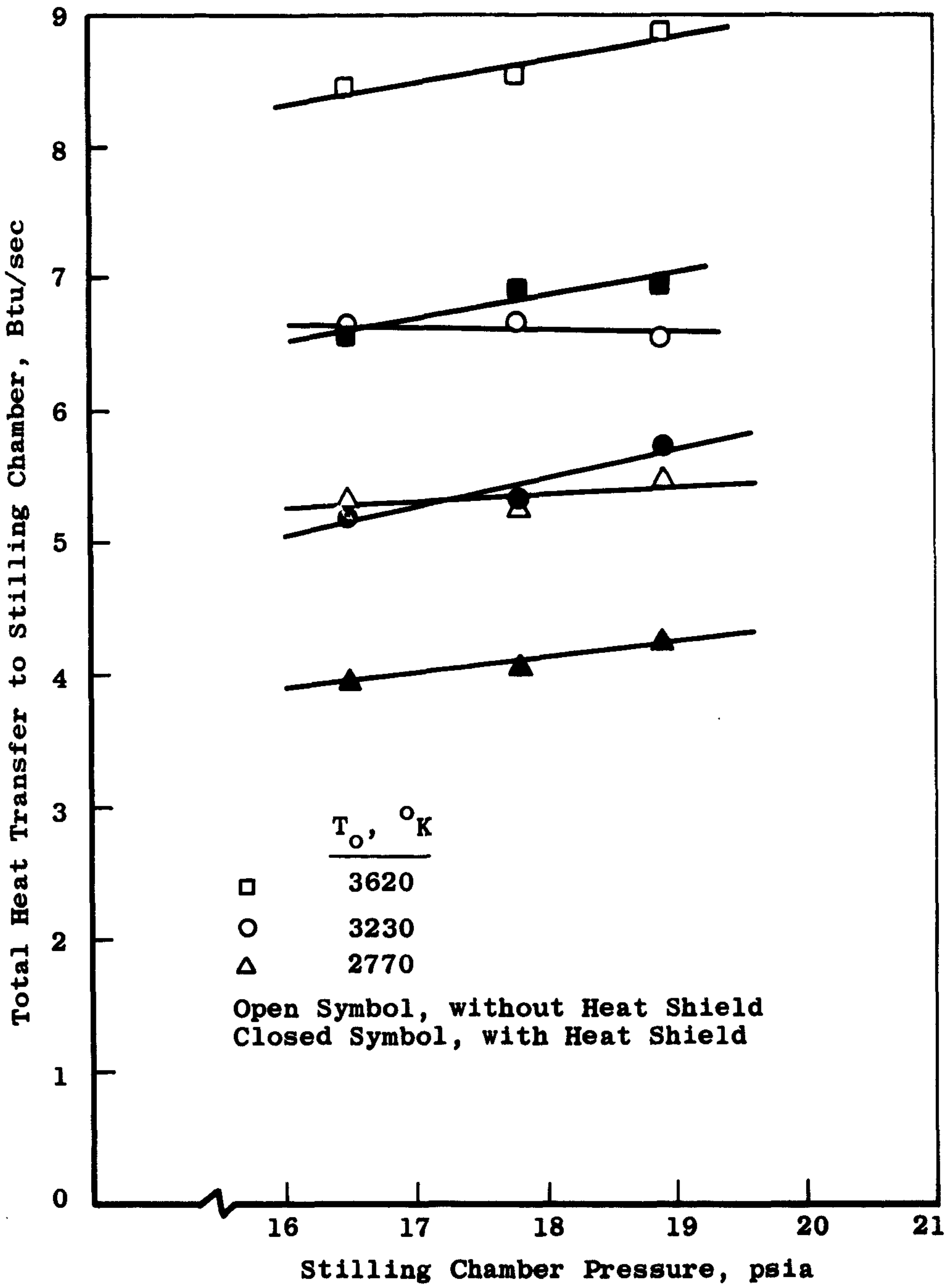


Fig. 12 Effect of p_o on Stilling Chamber Heat Transfer

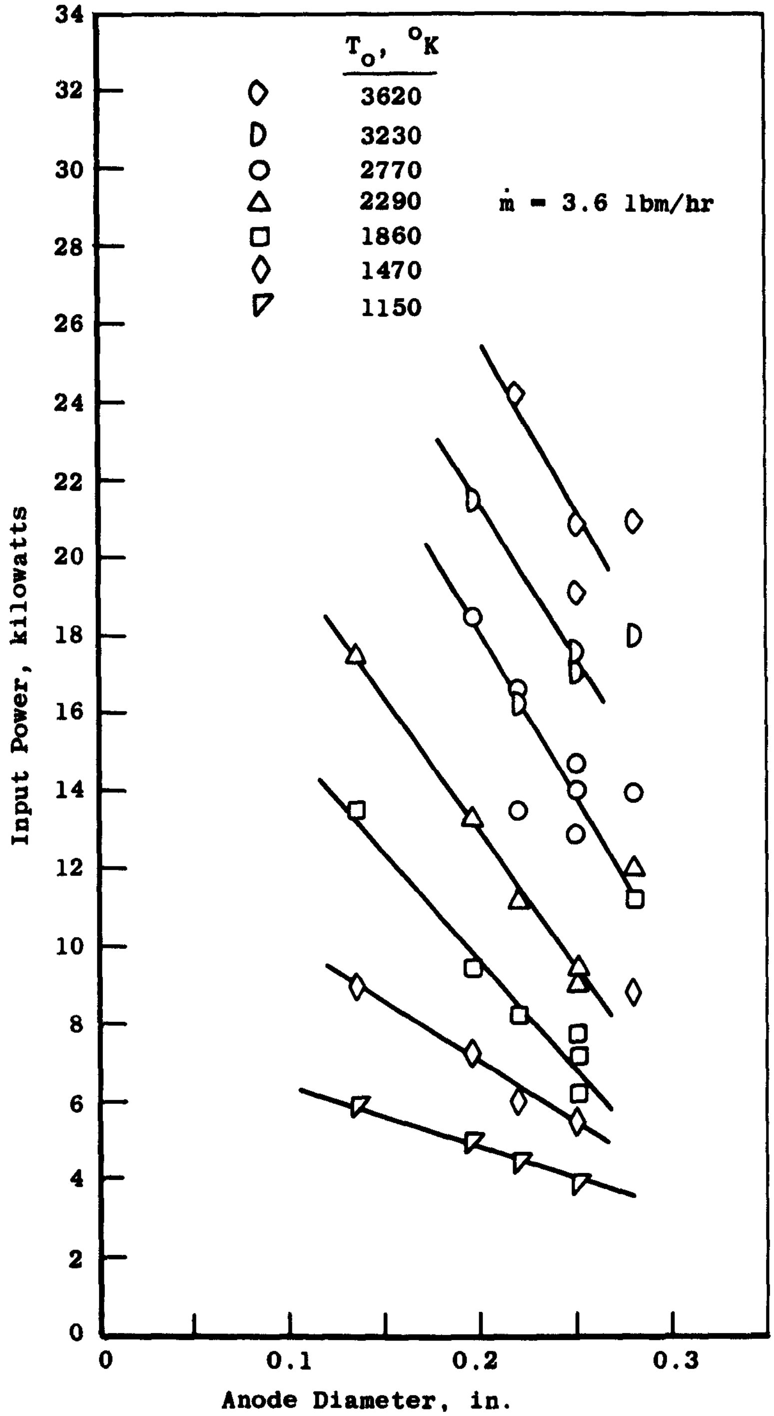


Fig. 13 Effect of Anode Diameter on Input Power without Heat Shield

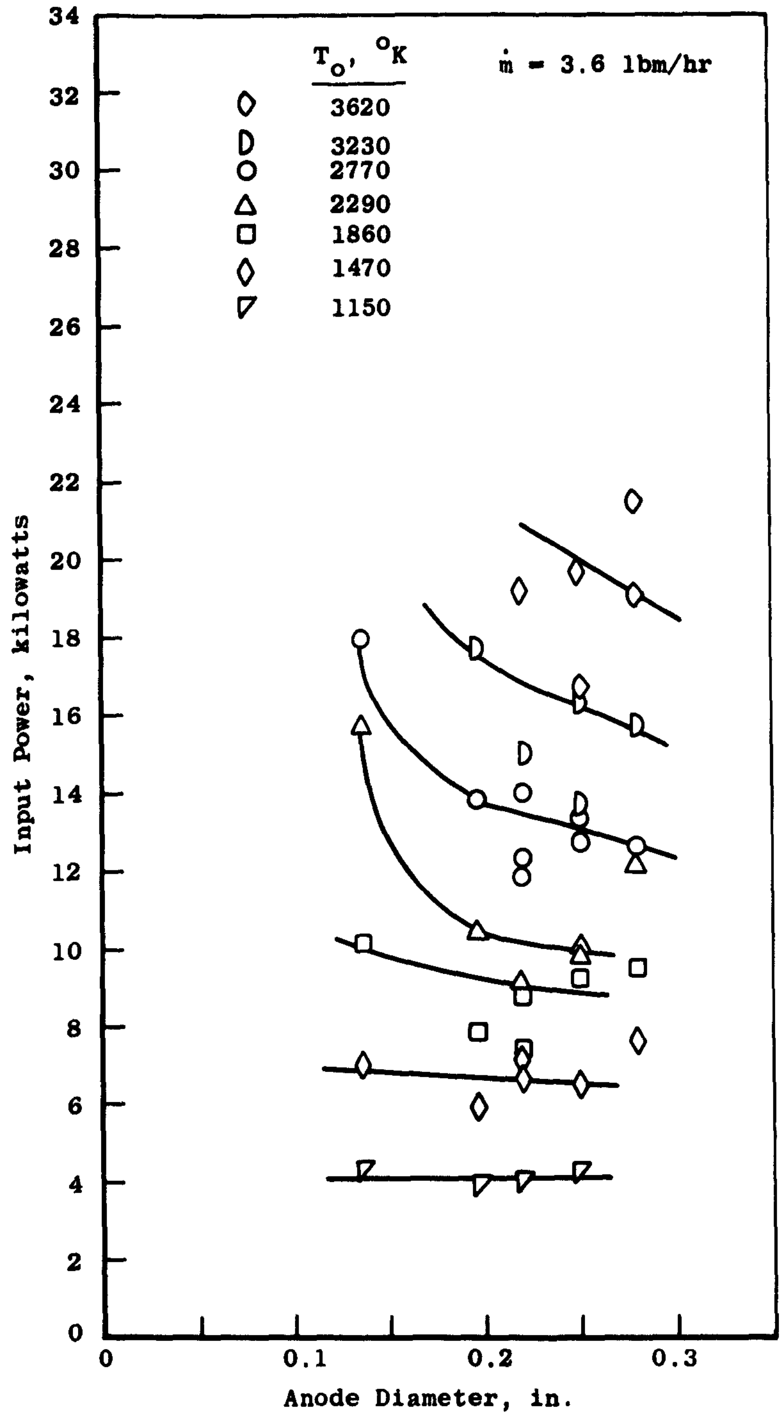


Fig. 14 Effect of Anode Diameter on Input Power with Heat Shield

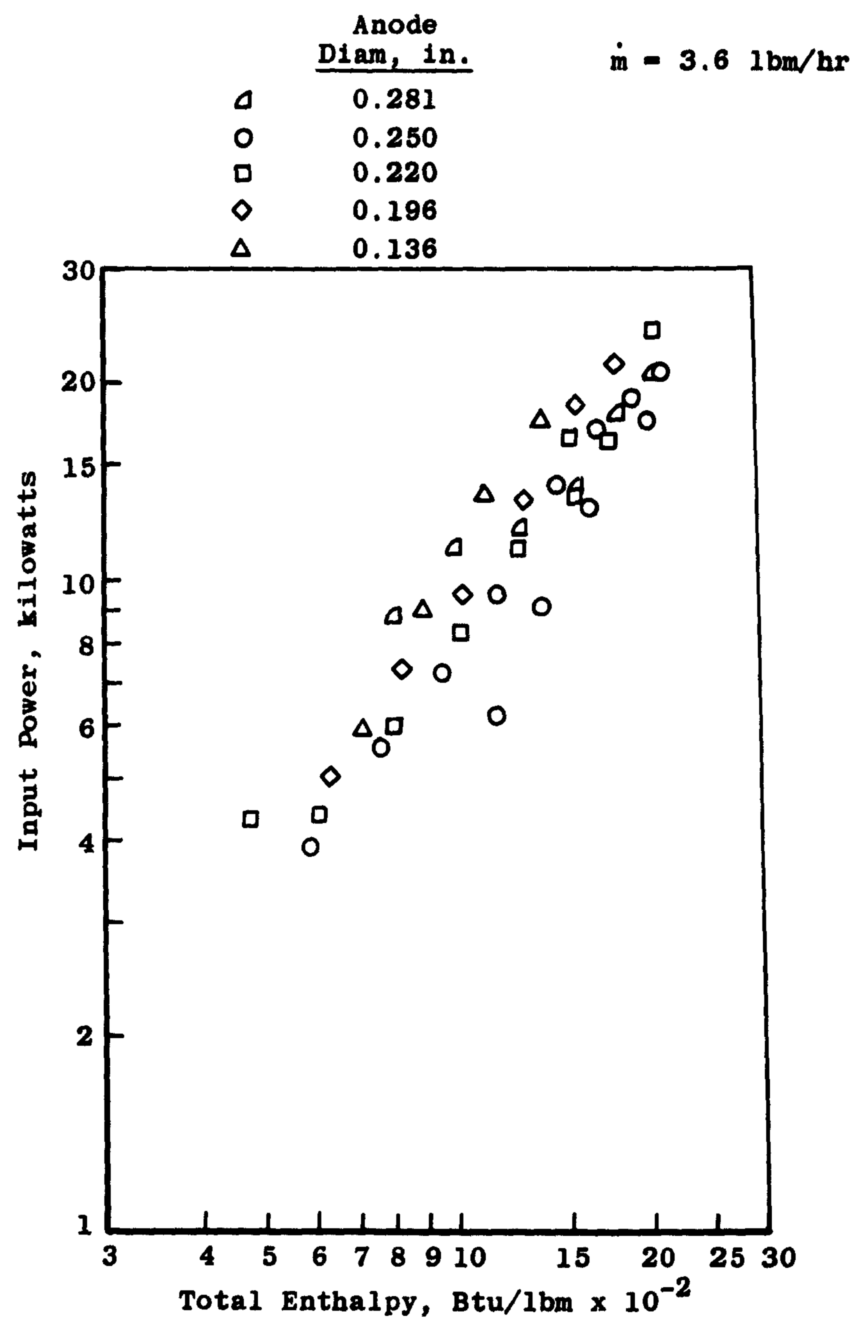


Fig. 15 Effect of H_o on Input Power without Heat Shield

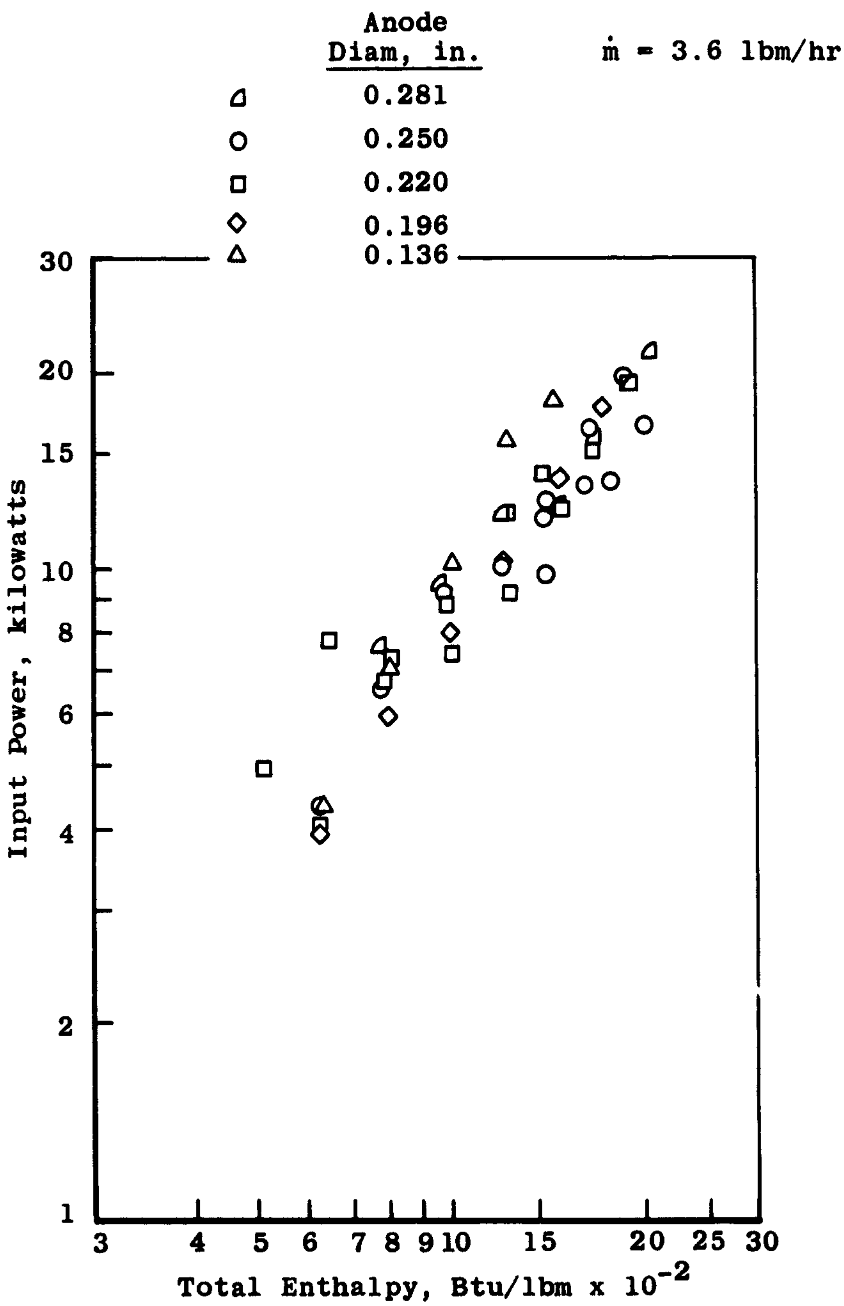


Fig. 16 Effect of H_o on Input Power with Heat Shield

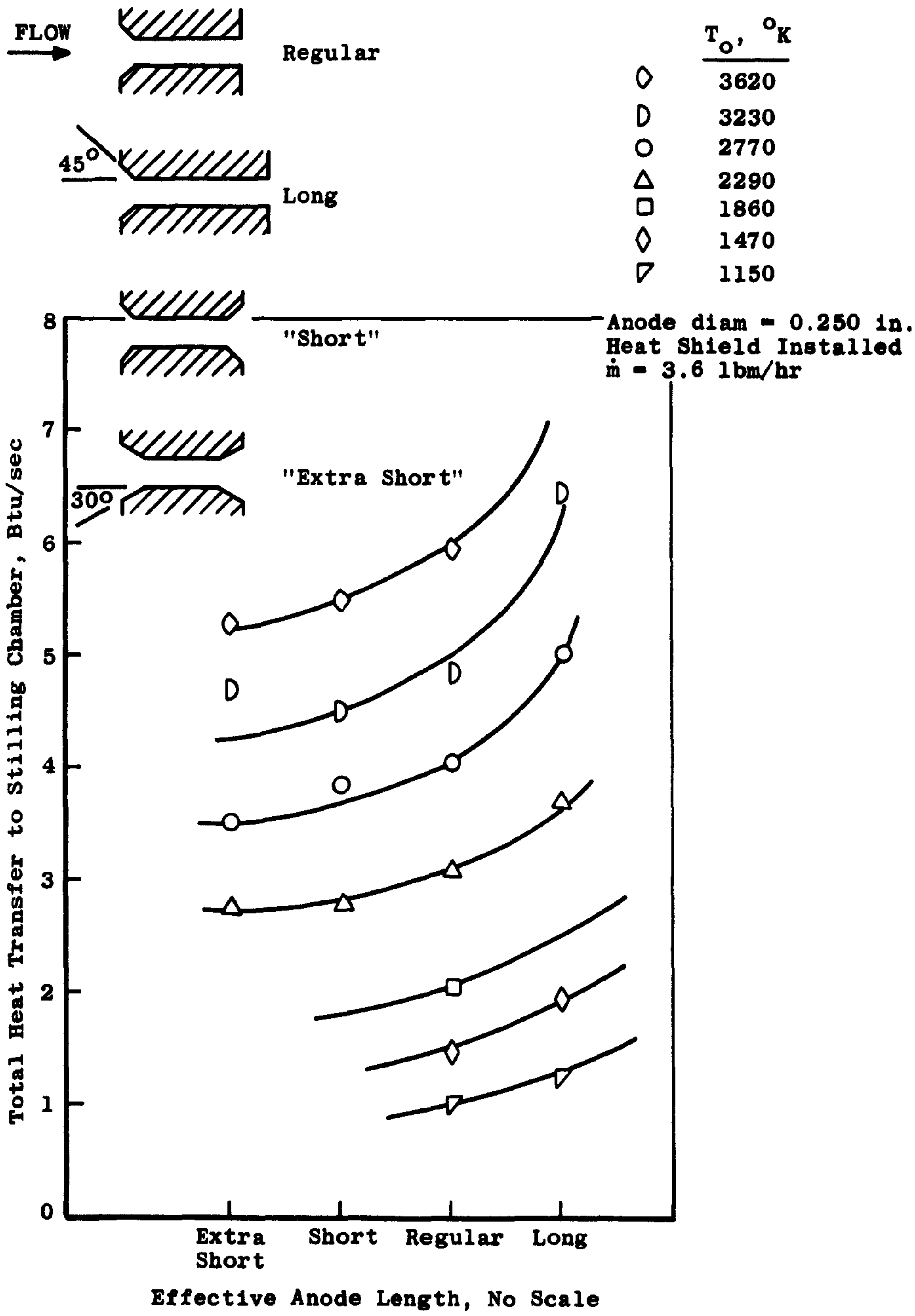


Fig. 17 Effect of Anode Length on Stilling Chamber Heat Transfer

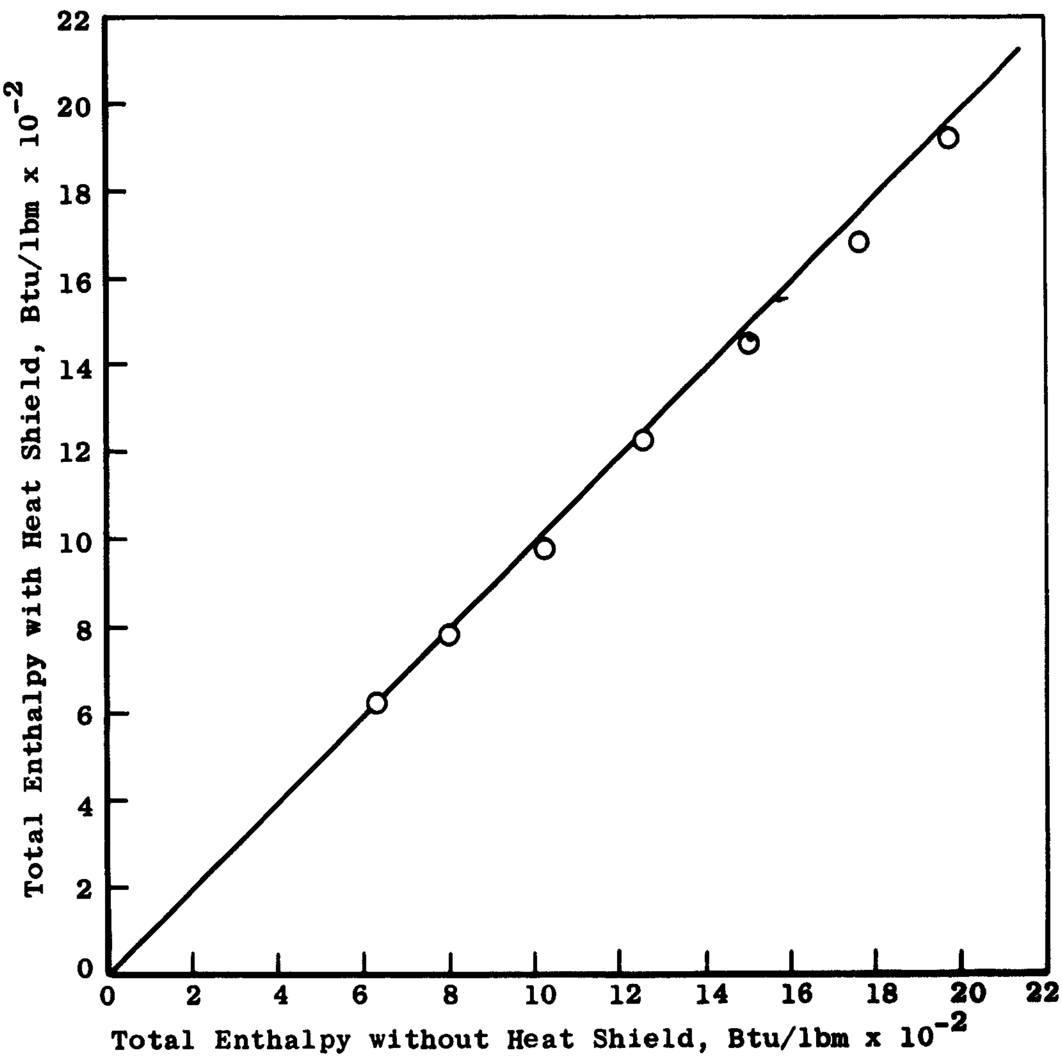


Fig. 18 Comparison of Total Enthalpy with and without Heat Shield

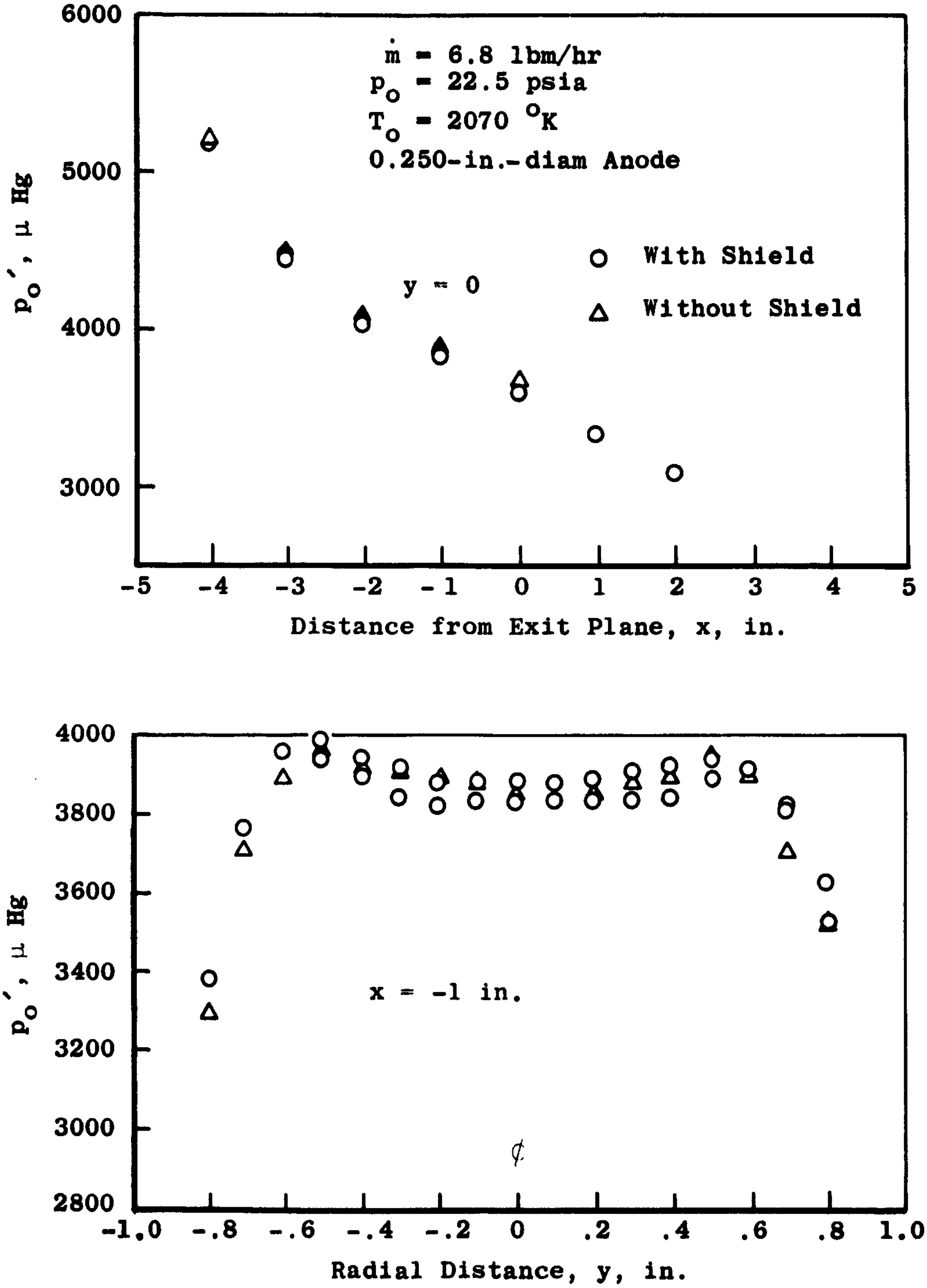


Fig. 19 Comparison of Impact Pressure in Nozzle with and without Heat Shield

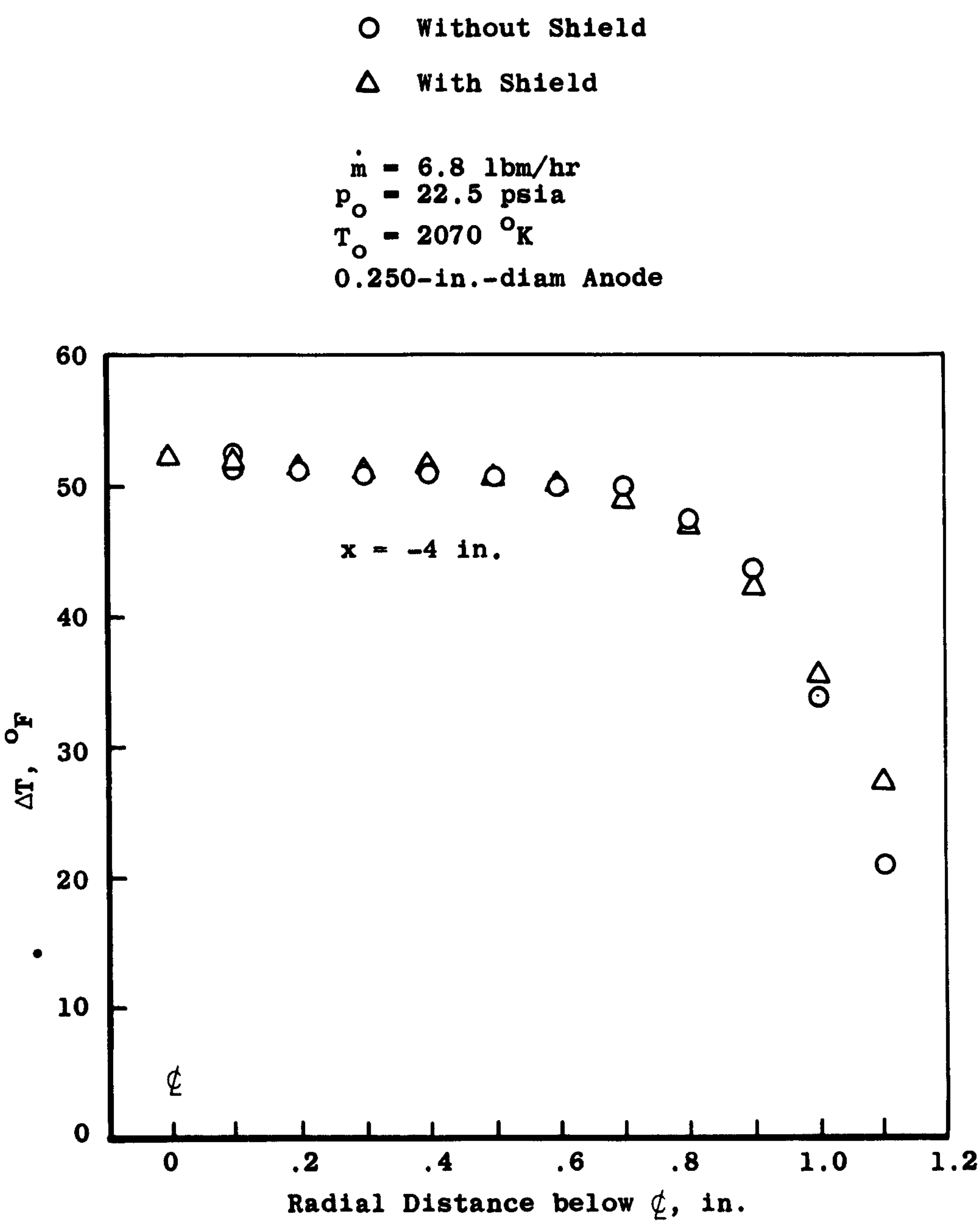


Fig. 20 Comparison of Heat Transfer to Stagnation Region of Hemisphere in Test Section with and without Heat Shield in Stilling Chamber

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Arnold Air Force Station, Tennessee
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1. Hypervelocity wind tunnels
2. Thermodynamics
3. Heat transfer
4. Calorimeters
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